Discovery of the Low-Redshift Optical Afterglow of GRB 011121 and Its Progenitor Supernova 2001ke[1]

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ABSTRACT

We present the discovery and follow-up observations of the afterglow of the Gamma-Ray Burst (GRB) 011121 and its associated supernova SN 2001ke. Images were obtained with the OGLE 1.3m telescope in $BVRI$ passbands, starting 10.3 hours after the burst. The temporal analysis of our early data indicates a steep decay, independent of wavelength with $F_\nu \propto t^{-1.72\pm0.05}$. There is no evidence for a break in the light curve earlier than 2.5 days after the burst. The spectral energy distribution determined from the early broad-band photometry is a power-law with $F_\nu \propto \nu^{-0.66\pm0.13}$ after correcting for a large reddening. Spectra, obtained with the Magellan 6.5m Baade telescope, reveal narrow emission lines from the host galaxy which provide a redshift of $z = 0.362 \pm 0.001$ to the GRB. We also present late R and J-band observations of the afterglow $\sim 7-17$ days after the burst. The late-time photometry shows a large deviation from the initial decline and our data combined with Hubble Space Telescope photometry provide strong evidence for a supernova peaking about 12 rest-frame days after the GRB. The first spectrum ever obtained of a GRB supernova at cosmological distance revealed a blue continuum. SN 2001ke was more blue near maximum than SN 1998bw and faded more quickly which demonstrates that a range of properties are possible in supernovae which generate GRBs. The blue color is consistent with a supernova interacting with circumstellar gas and this progenitor wind is also evident in the optical afterglow. This is the best evidence to date that classical, long gamma-ray bursts are generated by core-collapse supernovae.

Subject headings: gamma-rays: bursts — supernovae: general — supernovae: individual (SN 2001ke)

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1. INTRODUCTION

The origin of gamma-ray bursts (GRB) has been a mystery since their discovery in the 1960's. It has only been since the BeppoSAX satellite (Boella et al. 1997) began providing rapid, accurate localization of several bursts per year has it been possible to study these events and their afterglows in detail. Optical observations of afterglows (e.g. GRB 970228: Groot et al. 1997) have allowed redshifts to be measured for a number of GRBs (e.g. GRB 970508: Metzger et al. 1997), providing definitive proof of their cosmological origin. The unusually faint GRB 980425 associated with supernova 1998bw was the first direct evidence that at least some GRB result from the core collapse of massive stars (Galama et al. 1998). But other indirect evidence has come from studies of the location of GRB in their host galaxies (e.g. Holland & Hjorth 1999; Holland et al. 2000; Fynbo et al. 2000; Bloom et al. 2002a; Fruchter et al. 2002; Hjorth et al. 2002) and the types of galaxies that GRB prefer (e.g. Hogg & Fruchter 1999). A number of other GRB have shown deviations from a power-law decline (e.g. GRB 980326, Bloom et al. 1999), but these were at high redshift and any supernova component was difficult to study.

The very bright GRB 011121 was detected by BeppoSAX on 2001 November 21.78288 (UT) (Piro 2001a) and its position was quickly refined to $2'$ error radius (Piro 2001b). We began the effort to optically monitor the error circle with the 1.3m OGLE telescope starting 10.3 hours after the burst. A possible optical afterglow (OA) was quickly identified (Wyrzykowski, Stanek & Garnavich 2001) as a fairly bright ($R \approx 19.1$), new object not present in the Digitized Sky Survey image, at the position later determined by Price et al. (2001b): $\alpha = 11^h34^m29^s.67$, $\delta = -76^\circ01'41''.6$ (J2000.0). The source's rapid fading by ~ 0.5 mag during first ~ 3 hours of observations (Stanek, Garnavich, & Wyrzykowski 2001; Infante et al. 2001) strengthened its likely association with the GRB. Spectra of the optical afterglow were obtained 12 hours after the burst with the Magellan 6.5m Walter Baade telescope and narrow emission lines from the host galaxy gave a redshift of $z = 0.36$ (Infante et al. 2001). Infante et al. went on to note that the rapidly fading OA and the relatively low redshift of the GRB made this burst an attractive target to search for a possible underlying supernova. The afterglow was also detected in the infrared (Price et al. 2001a) and radio (Subrahmanyan et al. 2001).

Late-time imaging and spectra obtained with the Magellan telescope two weeks after the GRB suggested a slowing in the initial rapid decline of the OA or contamination from the host galaxy of the GRB. Hubble Space Telescope (*HST*) images taken two weeks after the burst and reported in March 2002 appeared to show the burst continuing to fade at the initial power-law rate (Bloom 2002). However, Garnavich et al. (2002) analyzed these same images and found that the point source was two magnitudes brighter than the extrapolation of the OA light curve and possessed colors inconsistent with a power-law spectrum, suggesting the presence of a supernova (SN 2001ke: Stanek et al. 2002). Later *HST* epochs confirmed the slow decline consistent with a supernova (Bloom et al. 2002b; Kulkarni et al. 2002).

Here we present our extensive data set on the optical afterglow and the associated supernova.

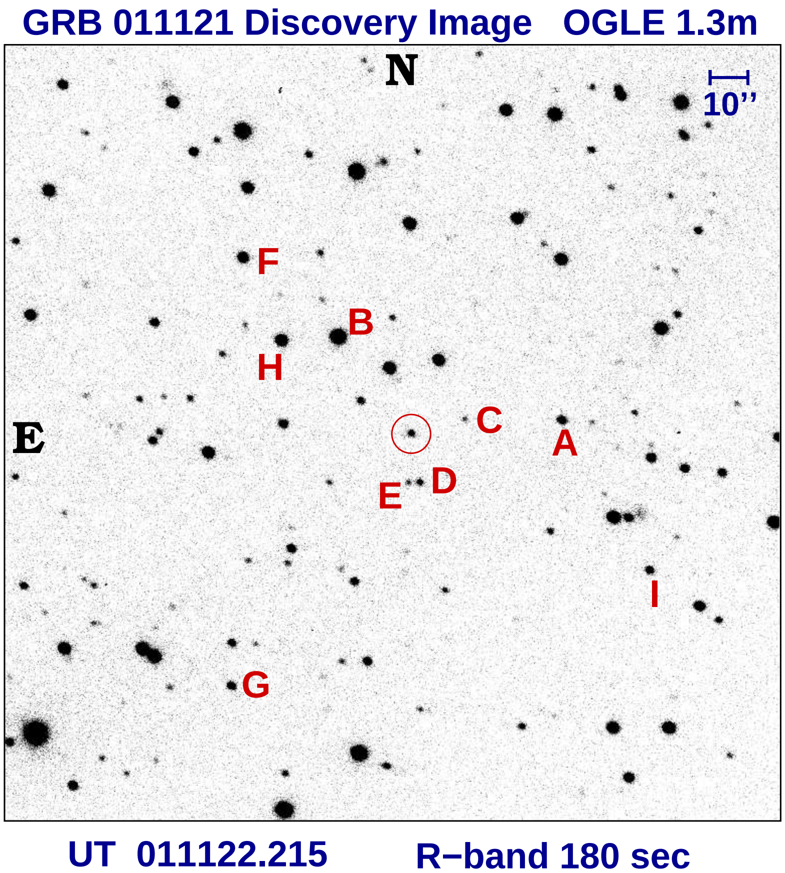

Fig. 1.— Discovery R-band image of the optical afterglow (circle) of GRB 011121, taken with the OGLE 1.3m telescope. The size of the field is 200″ on a side. Also marked are photometric comparison stars (see Table 1).

GRB 011121 has been also discussed in recent papers by Bloom et al. (2002c), Dado, Dar & De Rujula (2002) and Price et al. (2002).

2. THE PHOTOMETRIC DATA

2.1. *UBVRI* Photometry[9]

The majority of our photometric data were collected at two telescopes: the Optical Gravitational Lensing Experiment (OGLE: Udalski, Kubiak & Szymański 1997) 1.3m telescope at the Las Campanas Observatory and the Magellan 6.5m Walter Baade telescope at Las Campanas. The OGLE telescope was equipped with the 8k × 8k OGLE-III CCD mosaic, with a has a scale

[9]Analysis presented here supersedes our GCN Circulars: Wyrzykowski, Stanek, & Garnavich 2001; Stanek et al. 2001; Infante et al. 2001; Wyrzykowski & Stanek 2001; Stanek & Wyrzykowski 2001

of $0''.26$ per pixel. Most of the Magellan images were taken with the LDSS-2 imaging spectrograph in its imaging mode, with a scale of $0''.378$ per pixel. Magellan images on Nov. 24, Dec. 5 and 6 were taken with the DirectCam imager with a scale of $0''.069$ per pixel (unbinned). Fig. 1 shows the field containing the OA.

Photometry obtained with the CTIO-0.9m and 4m on Nov. 22 and 23 by Olsen et al. (2001) and Brown et al. (2001) were also added to our data set. The CCD images were kindly provided to us and we measured the OA magnitudes using the same methods as applied to the OGLE and Magellan data.

During the night of 2001 Nov. 22, the optical transient (OT) was observed with the MOSAIC-II camera (chip 2) on the CTIO 4m telescope, using *UBRI* filters (Brown et al. 2001). That night three standard fields (Landolt 1992) were also observed in all four colors. There were between 4 and 6 standard stars on the chip and we have made an independent calibration of the field stars around the GRB using this data. Aperture photometry was performed on the standard stars frames. We determined the zero point for each color using average air mass terms for CTIO. We used DoPHOT (Schechter, Mateo & Saha 1993) to extract the photometry of all stars on the frames containing the OT. We then determined an aperture correction for each frame using the same aperture as for the standard stars. These aperture magnitudes have been corrected for the zero point determined from the standards stars, accounting for the difference in air mass. Color terms between the CTIO filters and standard bandpasses were found to be small. We estimate that our calibration is accurate to ± 0.02 mag. Table 1 gives the derived magnitudes for the secondary standard shown in Figure 1.

2.2. *HST* Photometry

The Hubble Space Telescope Wide-Field/Planetary Camera 2 (WFPC2) observed the GRB 011121 field beginning two weeks after the burst (GO 9180, PI: Kulkarni). Photometry was performed on objects in the field using a 2-pixel radius aperture. Corrections were made for charge-transfer-efficiency (CTE) using the Whitmore-Heyer prescription (Whitmore & Heyer 1998) and for geometric distortion. Bright stars on the images were used to determine the correction to bring the measurement to an equivalent $0.5''$ aperture. All the data were then corrected to infinite aperture by subtracting 0.1 mag. Zeropoints on the Vega system were taken from the WFPC2 Data Handbook and the resulting magnitudes in the flight system bands are shown in Table 2.

To compare with ground-based R-band photometry the F702W magnitudes were converted to standard R using F555W−F702W color and the prescription of Dolphin (2000). Magellan R-band data obtained around the time of the first *HST* epoch are consistent with the converted F702W magnitude.

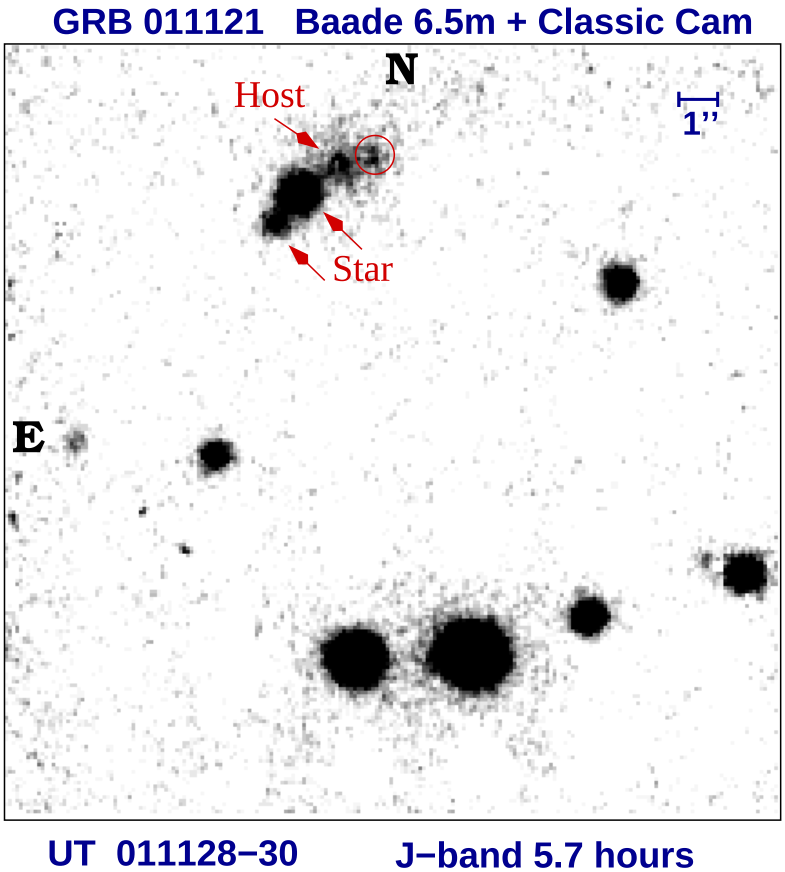

Fig. 2.— Infrared image of GRB 011121 taken with the Magellan 'Classic Cam'. The field is 20″ on a side and the small circle which marks the OA/SN has a 0.5″ radius. An infrared calibration of the two bright stars in the south are given in Table 1.

2.3. Near-Infrared Photometry[10]

We obtained deep J-band images during commissioning of the 'Classic Cam' instrument on the 6.5m Walter Baade Telescope. The instrument consists of a 256×256 pixel NICMOS3 array with image scale of 0.″094/pixel. Images were obtained on 2001 Nov. 29, 30 and Dec. 1 (UT) and were made up of 36, 64 and 72 individual 120s exposures respectively. Seeing on the first night was excellent and estimated at 0.5″, but this degraded to > 0.6″ for the final two nights. The average of the best seeing images from the three nights is shown in Figure 2. The host galaxy is clearly visible as well as two stars just to the east of the host. We determined the location of the OA by transferring the coordinates from the *HST* WFPC2 F702W images taken on 2001 Dec. 5 and noted that a faint source was present. Centroid determination on such a faint source results in unreliable photometry because the aperture tends to pick the brightest noise bump. So we fixed the position of the OA from the *HST* data and used DaoPhot II (Stetson 1987) and AllStar

[10] Analysis presented here supersedes our GCN Circular: Phillips et al. 2001.

(Stetson 1992) to perform PSF photometry on the OA.

Three infrared standard stars (Persson et al. 1998) were observed before and after the GRB and used to calibrate the two bright stars south of the host galaxy (see Table 1). The ClassicCam used a Js filter which is slightly narrower than the standard J-band, but color corrections are expected to be small (Krisciunas et al. 2001).

In order to determine if the detections of the OA in these images were real we ran a series of artificial star tests on the images from each night. We added ten artificial stars with magnitudes similar to that of the OA to each image. These stars were placed in regions where the background was similar to that of the OA. We then ran DaoPhot II/AllStar on these images in exactly the same way as we did for the original images and obtained magnitude estimates for each artificial star. This procedure was repeated for several sets of artificial stars with a range of input magnitudes. We derive a limiting magnitude of $J_{lim} \approx 22.4 \pm 0.2$ for the images. This suggests that the OA/SN was near the magnitude limit of the data.

We subtracted the stars and used aperture photometry to measure the brightness of the host. The host has $J = 19.8 \pm 0.3$ in an aperture with a radius of $4''$. We were unable to detect any light outside this aperture.

3. THE SPECTROSCOPIC DATA

Spectra of the OA were obtained with the Magellan 6.5m Walter Baade telescope using the LDSS-2 imaging spectrograph on 2001 Nov. 22.3 UT, $\approx$ 12 hours after the burst and again on Nov. 23.3, $\approx$ 36 hours post-burst. We used a slit width of $1''$ rotated to the parallactic angle which provided a resolution of 12 Å and coverage from 4000 to 9500 Å. Each night of observation consisted of two 1200s exposures on the OA as well as images of He-Ne comparison lamps and standard stars. The spectra were bias subtracted and flat field corrected using a normalized continuum lamp spectrum. The extracted spectra were then wavelength and flux calibrated. The spectrum taken on the first night showed a steep decline in flux toward the blue, which was not consistent with the second night's spectrum. By calibrating stars elsewhere on the long slit we found that these too had a blue deficit which was not accounted for by the flux standards. We concluded that vignetting within the spectrograph had partially blocked the shorter wavelengths and that the flux calibration of the GRB that first night was compromised.

Spectra of the OA taken on Nov. 23 showed a smooth continuum with no strong features as expected from a power-law source. Weak, narrow emission lines were detectable in spectra from both nights. Since the photometry showed little color change between the two nights, we used the Nov. 23 spectrum to correct the vignetting in the Nov. 22 data and combined all the spectra to maximize the signal-to-noise. The resulting spectrum with the OA continuum removed is shown in Figure 3. Narrow emission features associated with HII regions in the host galaxy are clearly present and they provide a redshift of $z = 0.362 \pm 0.001$. The line that we identify as HeI 5875 Å

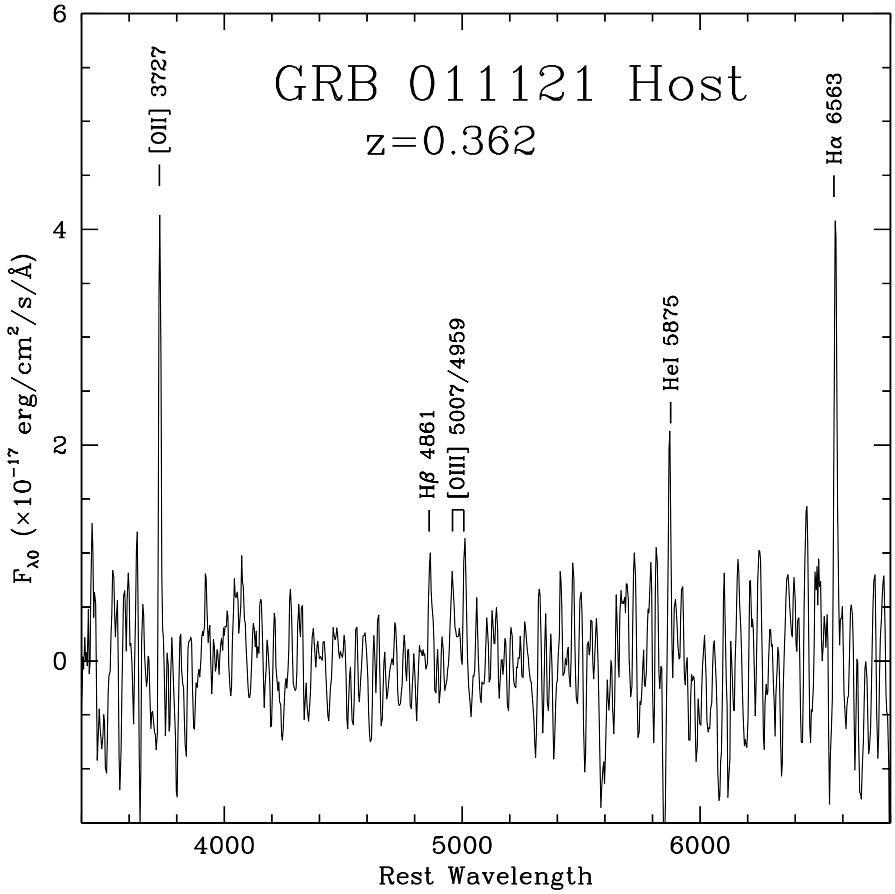

Fig. 3.— The spectrum of the GRB plus host galaxy obtained within the first two days of the burst. The continuum has been fit with a polynomial and subtracted leaving only emission lines from the host.

is stronger than normally seen in typical HII regions.

Late-time spectra were again obtained with the Magellan LDSS-2 spectrograph on Dec. 7.3, $\approx$ 15 days after the burst when the supernova light dominated over the OA flux. The $1''$ slit was rotated to include the faint star $2.5''$ to the south east of the OA and the host galaxy (see Figure 2). The spectra were obtained to confirm the redshift of the host galaxy as the supernova had not been reported. Two 900s exposures were taken and reduced in the same way as the early spectra. The seeing was good and this permitted the two point sources to be extracted separately. Fortunately the slit included the position of SN 2001ke and the resulting spectrum is the first of a supernova associated with a cosmological GRB (Figure 8).

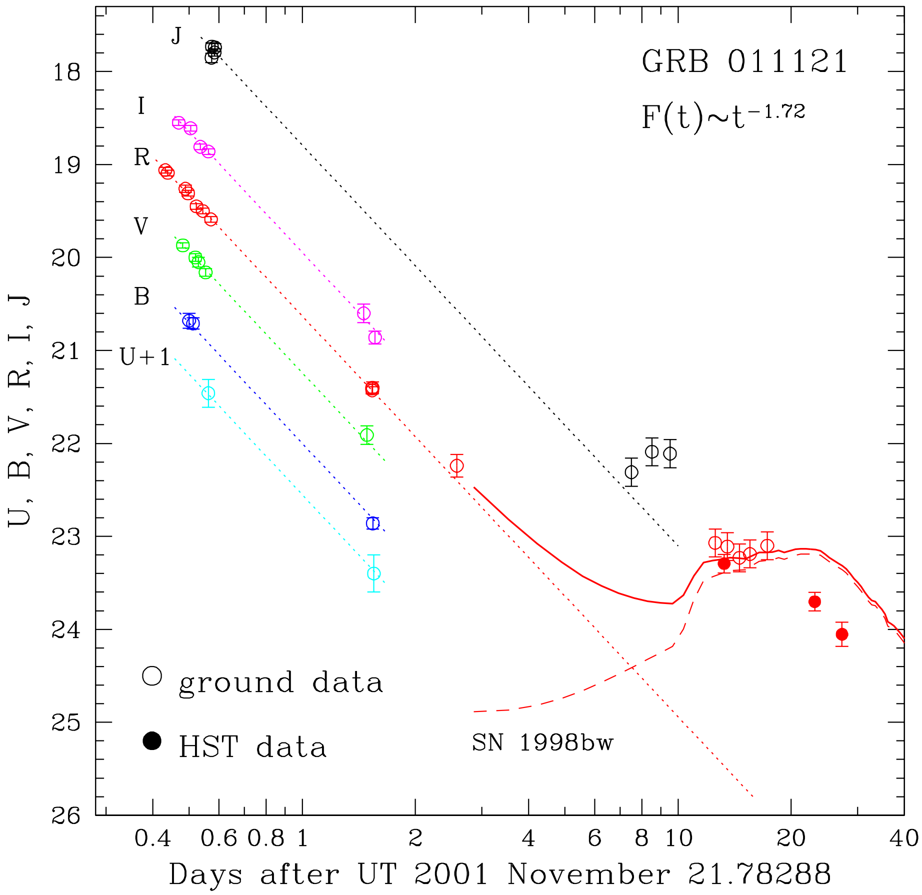

Fig. 4.— $UBVRIJ$ light curves of GRB 011121. A majority of these data derive from this paper, with additional $UBVRI$ data from Olsen et al. (2001) and Brown et al. (2001) (see Table 2) and early J-band data from Price et al. (2002). Also shown are three *HST* F702W epochs converted to the standard R-band. Dotted lines show the OA power-law decay and the dashed line is the light curve of SN 1998bw redshifted to $z = 0.36$, converted to the R-band, corrected for extinction and scaled by 0.1 mag. The solid line shows the combination of the OA and SN 1998bw.

4. PROPERTIES OF THE OPTICAL AFTERGLOW

4.1. The GRB Temporal Behavior

We plot the GRB 011121 $UBVRI$ light curves in Figure 4. Majority of these data come form this paper, with additional $UBVRI$ data from Olsen et al. (2001) and Brown et al. (2001) which we reduced independently to be consistent with our other photometry (see Table 2). In order to asses the importance of our late J-band data, we also show some early J-band data from Price et al. (2002). Also shown are three *HST* F702W epochs converted to the standard R-band.

The OT decays relatively quickly in early time, without a clear break (unlike many GRBs observed since GRB 990510: Stanek et al. 1999) or other deviations from smooth decay, such as observed in GRB 000301C (e.g. Garnavich, Loeb & Stanek 2000) or GRB 011211 (Holland et

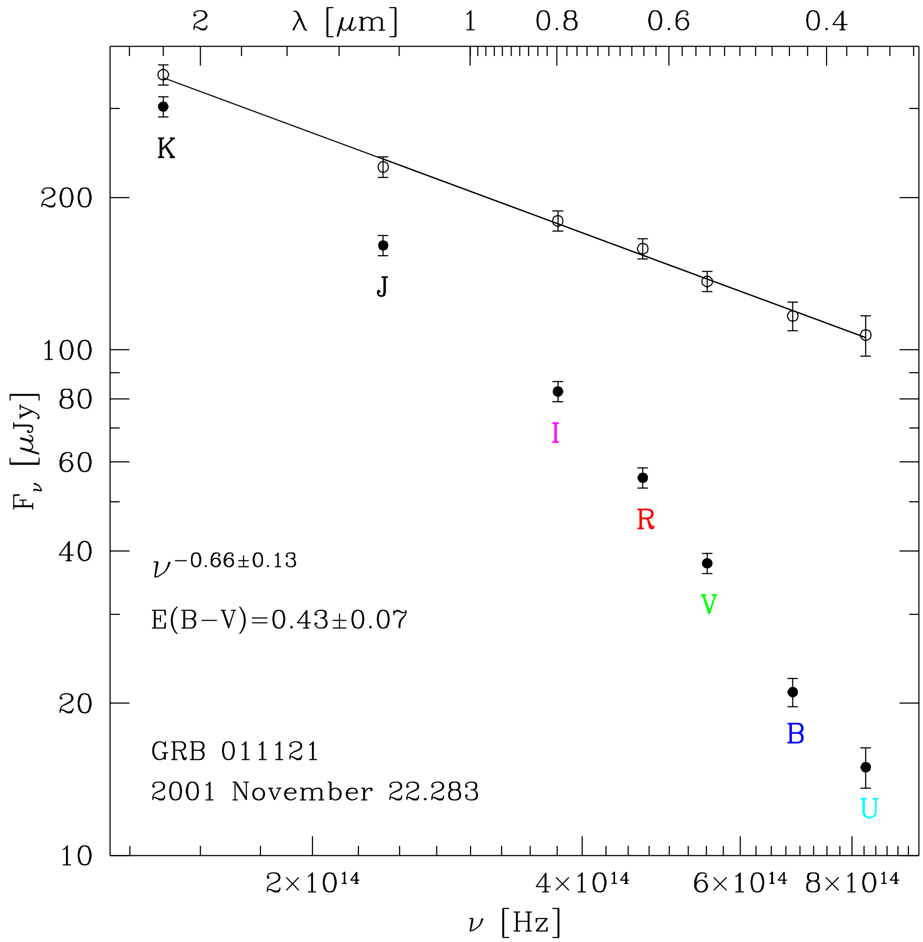

Fig. 5.— Synthetic broad-band spectrum of GRB 011121 12 hours after the burst, constructed using analytical fits shown in Figure 4. The open symbols show the best fit power-law which occurs for an E$(B-V) = 0.43$.

al. 2002). To determine the early temporal behavior of the OA, we have decided to fit only the data taken earlier than 2 days after the burst. There are 26 such $UBVRI$ points, and as can be seen in Figure 4 a single power-law $t^{-1.72\pm0.05}$ fit to these early data is excellent, with the resulting $\chi^2/DOF = 0.6$.

4.2. The GRB Broad-Band Spectral Energy Distribution

GRB 011121 is located at Galactic coordinates of $l = 298\overset{\circ}{.}2323, b = -13\overset{\circ}{.}8633$, in a heavily reddened direction, according to the map of Schlegel, Finkbeiner & Davis (1998, hereafter: SFD). The SFD Galactic reddening towards the burst is large, $E(B-V) = 0.50$, and such large reddenings tend to be overestimated in the SFD maps (e.g. Stanek 1998).

To make an independent estimate of the extinction we assume that the intrinsic energy

distribution of the OA is a power-law and find the extinction that gives the best match to a single power-law index. We first synthesize the $UBVRI$ spectrum from our data by interpolating the magnitudes to a common time. As discussed in the previous section, the optical colors of the GRB 011121 counterpart do not show significant variation during the first day. We therefore select the epoch of November 22.283 UT (12.0 hours after the burst) for the color analysis. We convert the $UBVRI$ magnitudes to fluxes using the effective frequencies and normalizations of Fukugita, Shimasaku & Ichikawa (1995). These conversions are accurate to about 3-4%, so to account for the calibration and interpolation errors we assign to each flux a 5% error (7% for the B-band and 10% for the U-band). To get further leverage on the reddening, we add the J and K observations of Price et al. (2002) scaled to the fiducial time and converted to fluxes using effective wavelengths and normalizations of Megessier (1995). We then determine how well a single power-law fit the dereddened fluxes using the χ^2 parameter and varying the total extinction assuming the standard reddening curve of Cardelli, Clayton & Mathis (1989), as tabulated by SFD (their Table 6). We find a best fit power-law at $\mathrm{E}(B-V) = 0.43 \pm 0.07$ (one sigma) and adopt this as the reddening to the OA. This technique lumps together Galactic and host galaxy extinction, however, our adopted value is one sigma lower than the SFD extinction, which implies Galactic reddening strongly dominates over the host contribution. Our value is slightly higher than that obtained by Price et al. (2002), most likely due to the somewhat different calibration of the optical data.

Under the assumption that the OA spectrum is a single power-law, the best fit spectrum is $\nu^{-0.66\pm0.13}$. The observed and corrected broad-band spectra are presented in Figure 5.

5. LATE-TIME PHOTOMETRY

We searched for a late-time recrudescence in the OA by R-band imaging with Magellan between 12 and 17 days after the burst. Subtracting these images with each other revealed no significant variation at the location of the OA suggesting that the host galaxy dominated the emission. When the *HST* data was publicly released it was clear that a point source was present which was two magnitudes brighter than the extrapolated light curve of the OA (Garnavich et al. 2002). The position of the source was determined from seven USNO A.2 stars on the WFPC2 chips and found to be 11:34:29.64 −76:01:41.51 with an error of $0.2''$ (Stanek et al. 2002). This is consistent with the position of the optical afterglow determined by Price et al. (2001b) based on the same astrometric catalog.

To remove host galaxy contamination in the late-time Magellan images we used the *HST* data as a template. After drizzling each epoch of F702W imaging we employed DaoPhot II (Stetson 1987) to subtract the point-spread-function (PSF) of the source. The three epochs were then combined, smoothed and rebinned to create a high signal-to-noise template image. Each Magellan image was then shifted to the coordinates of the template and the template convolved to match the PSF of the ground-based image. The difference between the image and the template then gives the uncontaminated brightness of the OA. The derived magnitudes are given in Table 2

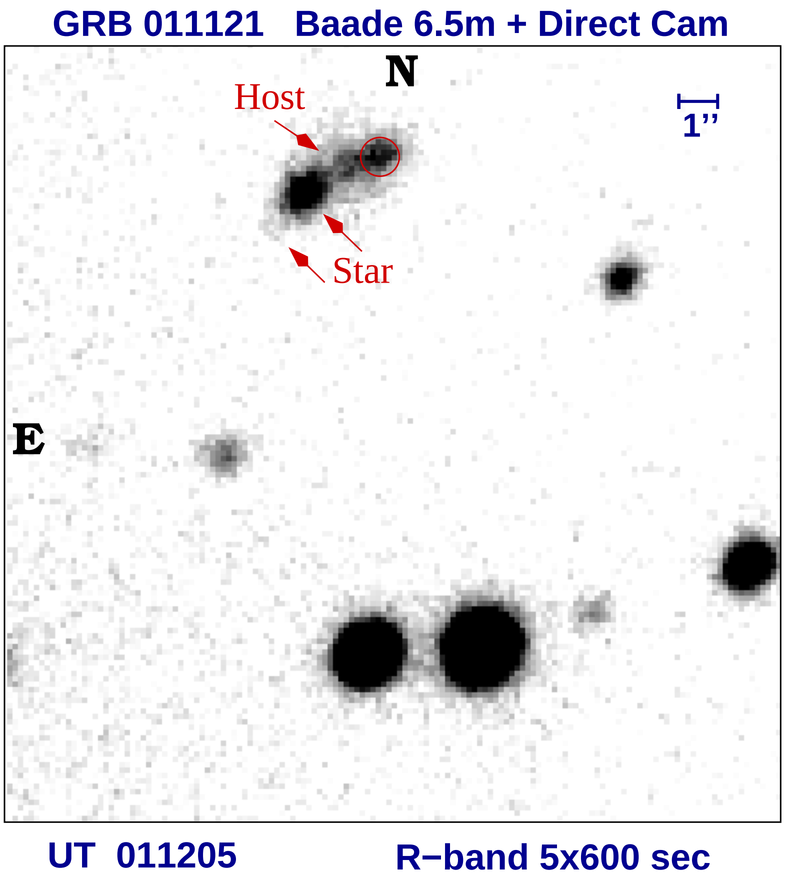

Fig. 6.— R-band image of GRB 011121 on 2001 Dec. 5 taken with Magellan and Direct Cam. The circle marks the position of the OA/SN.

and plotted in Figure 4.

6. DISCUSSION

6.1. GRB Properties

For a redshift of $z = 0.36$ and assuming a flat cosmology with $\Omega_m = 0.3$ and $H_0 = 65$ km s^{-1} Mpc^{-1}, the GRB was at a luminosity distance of 2.07 Gpc. This is the nearest OA with a determined redshift. The GRB 980425 associated with SN 1998bw was at a redshift of $z = 0.009$, but did not have a detected optical afterglow. The fluence of GRB 011121 in the 25-100 keV band of Ulysses was 2×10^{-5} erg cm^{-2} (Hurley et al. 2001), which corresponds to an isotropic energy output of $2.7{\times}10^{52}$ erg after correction to a rest frame 20-2000 keV energy band (Bloom et al. 2001). This is at the low end of the isotropic energies listed in the compilation by Frail et al. (2001) but not at all unusual.

The R-band light curve of the OA shows no evidence for a break from the time of discovery

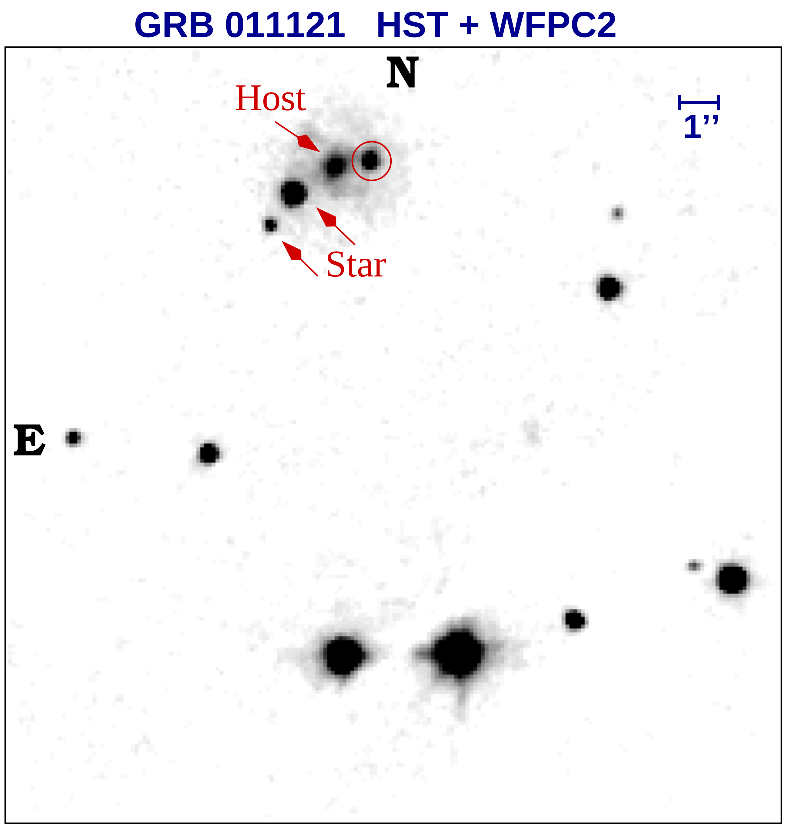

Fig. 7.— Average of F555W, F702W and F814W *HST* images from all the available epochs. The extent of the host galaxy is shown as well as a hint of spiral structure.

to 2.5 days after the burst. If a break occurred later than 2.5 days then the low isotropic energy implies a jet opening angle of $\theta > 6^\circ$. Radio observations reported by Price et al. (2002) appear to support a late break. Correcting for the beaming fraction, this burst would then have a total energy similar to the 'standard energy' for GRB of 5×10^{50} erg suggested by Frail et al. (2001).

The index of the optical light curve power-law decay was high compared to most pre-break indices, but is typical for post-break decay rates. The observed $\alpha = 1.72$ and $\beta = 0.66$ are best fit by a jet shocking a uniform density medium (ISM) and is a poor fit to an isotropic shock into an ISM (Sari, Piran, & Halpern 1999). Placing GRB 011121 on Fig. 3 of Stanek et al. (2001) suggest this OA was observed post-break and implies the index change occurred earlier than 10 hours after the burst. An early break means a smaller opening angle of $\theta < 3^\circ$, and an energy more than 10 times lower than a standard burst.

The very low-redshift burst associated with SN 1998bw had an isotropic energy well below the 'standard' energy proposed by Frail et al., and GRB 980326, the other cosmological burst with a well-established association with a supernova, was under-luminous compared to the 'standard' energy (Frail et al. 2001). But the numbers of events directly associated with supernovae are too small to link them with subluminous GRB.

If the break occurred after 2.5 days, then the steep light curve decay and flat spectral indices observed in GRB 011121 OA are better matched to a burst into a stratified medium instead of a uniform density gas (Chevalier & Li 2000). For a circumstellar density falling as r^{-2}, the observed $\beta = 0.66$ should result in a steep light curve index of $\alpha \approx 1.5$ in the slow cooling regime. The ISM case predicts a more shallow $\alpha \approx 1.0$. The possibility of a circumstellar wind has been noted by Price et al. (2002). The presence of a supernova at late times appears to bolster the picture of a stratified circumburst enviroment produced by a stellar wind.

6.2. SN 2001ke: A Supernova of a Different Color

The late-time photometry shown in Figure 4 clearly shows a deviation from the OA power-law decay. A similar bump was detected in GRB 980326 (Bloom et al. 1999) and attributed to a supernova although a light echo has also been proposed to explain these deviations (Esin & Blandford 2000). The combination of the fading OA and slowly rising supernova resulted in a nearly constant brightness for the combined light during our December imaging. The uncertainty in the brightness distribution of the host galaxy along with the nearly constant magnitude prevented us from detecting the supernova until the *HST* data became available to the public.

The first epoch *HST* photometry of the supernova was surprising for having a F555W-F702W color which was very blue. The initial SN color was, in fact, similar to the OA color and this comparison is independent of the assumed reddening. A type Ic supernova, even an unusually energetic one like SN 1998bw is fairly red compared to the power-law spectrum of most OA. Our spectrum, shown in Figure 8, confirms the large UV flux when compared to SN 1998bw. The 'red bump' thought to be characteristic of a supernova is really blue in the case of GRB 011121. It is only in the later *HST* photometry that the supernova turns red as is characteristic of SN past maximum.

The colors of SN 2001ke are more typical of a type IIn events which interact with circumstellar gas and have narrow and intermediate width hydrogen emission lines in their spectra (Schlegel 1990). As an example we compare the spectral energy distribution (SED) of SN 2001ke with the nearby type IIn supernova 1998S in Figure 9. Clearly the first *HST* epoch is similar to the SN 1998S SED near maximum and both supernovae redden within a few days. Note that the infrared varies little over the observation period as the maxima are very broad in the infrared. SN 1998S showed Wolf-Rayet features in the early spectra and was likely the core-collapse of a very massive star (Lentz et al 2001). We do not claim that SN 1998S is identical to the GRB 011121 supernova, only that the color history of these two events are similar and suggest circumstellar material was present. This is consistent with the OA behavior which implied a stratified circumstellar gas distribution.

The light curve of SN 1998S evolves much more slowly that SN 2001ke and this is true for most type II events with large hydrogen envelopes. But we also note, in contrast to Bloom et al.

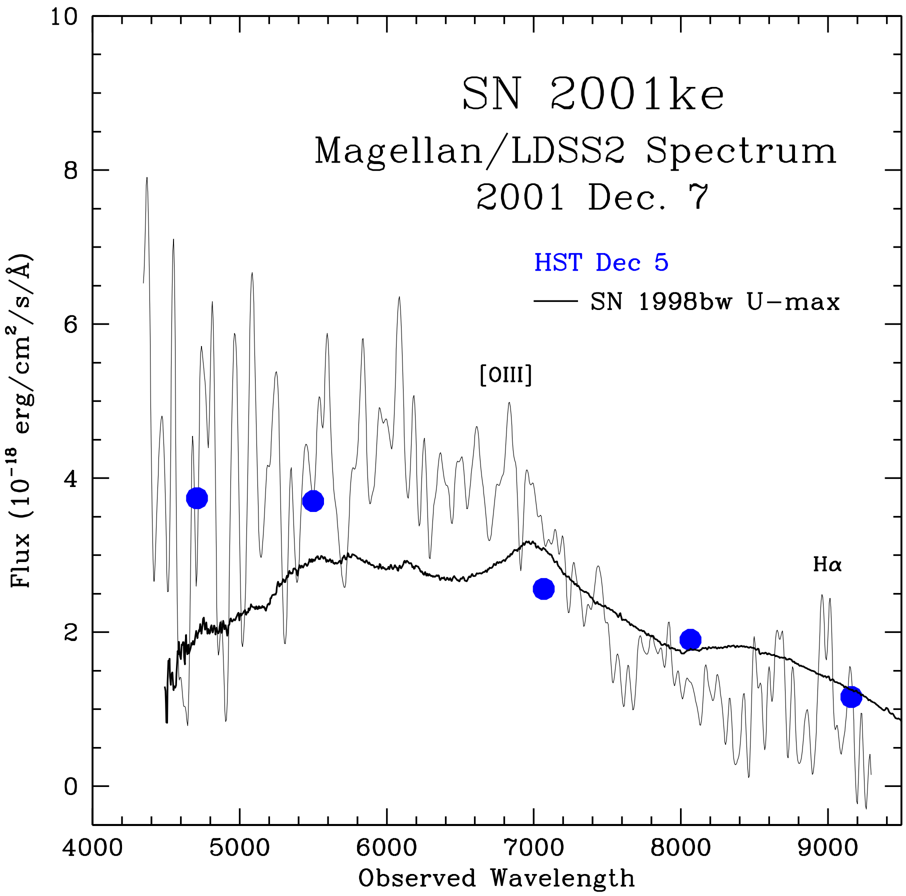

Fig. 8.— The spectrum of supernova 2001ke taken December 7 (UT) with the LDSS2 spectrograph on Magellan. The spectrum has been smoothed with a 30Å FWHM Gaussian kernel and corrected for extinction. For comparison, the *HST* broad-band flux measurements from December 5, also corrected for extinction, are shown as large circles. There are no obvious supernova features in the spectrum, but a comparison with SN 1998bw at the time of U-band maximum light (Galama et al. 1998) and corrected for $A_V = 0.2$ mag suggests that supernova features would be difficult to detect given the signal to noise ratio of the data

(2002c), that the light curve of SN 1998bw is a poor match to SN 2001ke. After correcting for the time dilation at $z = 0.362$, SN 2001ke evolves 40% faster around 5000Å than 1998bw (see Figure 4) assuming the clock started for both at the time of the gamma-ray burst.

There is a wide range of type IIn behavior. For example, the blue color of the type IIb SN 1993J lasted for only a few days due to its unique distribution of circumstellar material (Garnavich & Ann 1994). Certainly SN 2001ke could have been a type Ib/c which was dominated by circumstellar emission early on. SN 1997cy (Germany et al. 1998) was a type IIn event which also may have been associated with a GRB (GRB 970514).

The apparent rapid fading of SN 2001ke could also be explained if we remove the assumption that the GRB occurred at core-collapse. There is some evidence from X-ray spectra that metal-rich

material surround some GRB (e.g. Antonelli et al. 2000) which seems to imply that the associated supernova exploded weeks to months before the gamma-ray emission. In the case of GRB 011121, the time delay between core-collapse and gamma-rays would only be on the order of days to match SN 1998bw light curve.

Converting the SN 1998bw light curve to the R-band at $z = 0.362$ give a peak brightness 1.3 mag less than the SN 2001ke observations. Our adopted extinction of 1.13±0.18 in the R-band suggests SN 2001ke was similar in absolute brightness to SN 1998bw which had a $M_V = -19.35$ (Galama et al. 1998). We estimate an absolute brightness of SN 2001ke near maximum of $M_V = -19.2 \pm 0.2$ with most of the uncertainty due to the large extinction correction.

From the *HST* images the host appears as a face-on spiral galaxy with the GRB/SN offset $0.88''$ or 4.8 kpc from the center in a low-Ω_m flat cosmology. The [OII] flux is an good indicator of the star formation rate. After correction for Galactic extinction and using the Balmer lines to correct for an average host extinction, we find a [OII] luminosity of $2.0{\times}10^{41}$ erg s^{-1}. We convert this to a star formation rate using the relation given by Kennicutt (1998). The slit did not cover the entire galaxy so the total flux is uncertain, but roughly corresponds to a star formation rate between 3 and 6 M$_\odot$ yr^{-1}.

7. CONCLUSIONS

We have identified the OA associated with GRB 011121 and found its light curve is well fitted by a single power-law decay with an index of $\alpha = 1.72 \pm 0.05$ between 10 hours and 2.5 days after the burst. The broad-band spectrum of the OA over this time period is well matched by a single power-law with index $\beta = 0.66 \pm 0.13$ from 0.35 to 2.2 μm. We find that the reddening in the direction of the OA is large, E$(B-V)$=0.43±0.07. Our early spectra reveal emission lines from the GRB host galaxy which provide a redshift of $z = 0.362 \pm 0.001$. Except for the unusual GRB 980425, this is the nearest GRB with a well determined redshift.

Our observations two weeks after the GRB reveal a source two magnitudes brighter than expected from the OA decline. We show that this light is likely from a supernova which was the progenitor of GRB 011121. We obtained the first spectrum of a supernova associated with a cosmological GRB. The spectrum combined with colors from *HST* photometry show this emission to be intrinsically blue, but becoming more red as the supernova fades. The colors are not consistent with a typical type Ic and are too blue for the "hypernova" SN 1998bw. However the color can be explained by the supernova interacting with its circumstellar environment as was the case in SN 1998S and suggests the supernova classification may be IIn. Presence of circumstellar gas at the time of the supernova implies that the GRB was not isotropic and must have left circumstellar material for later interaction with the supernova.

The light curve of SN 2001ke appears to have peaked 10 to 12 rest-frame days after the GRB while SN 1998bw reached maximum some two weeks after GRB 980425. The time evolution

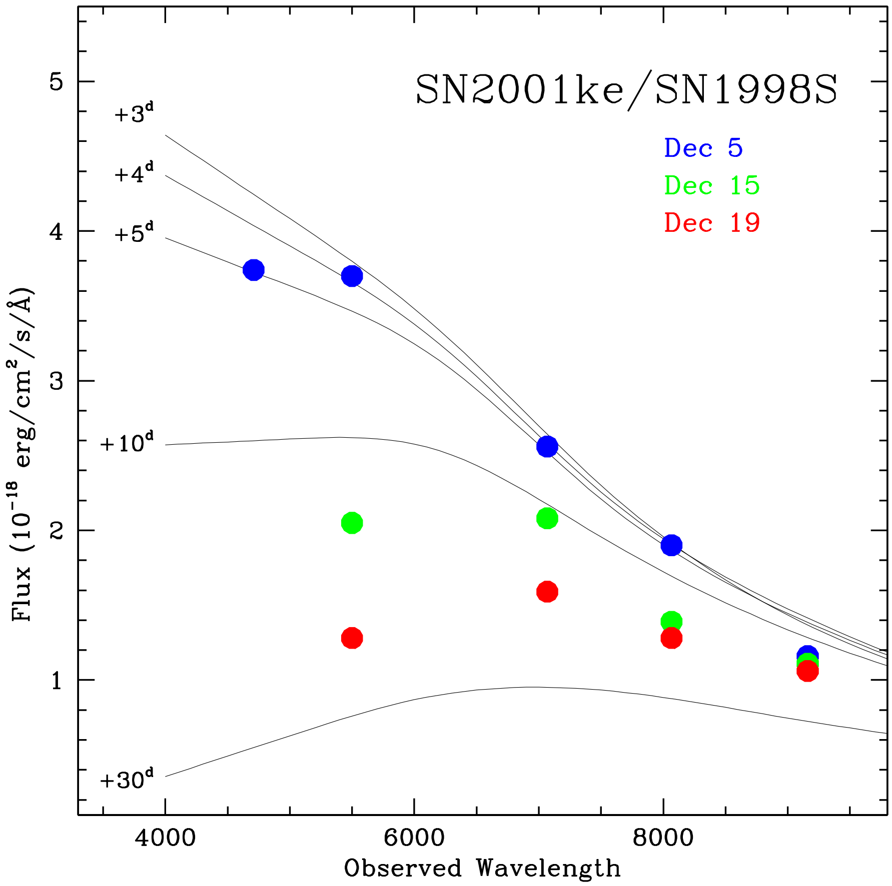

Fig. 9.— The *HST* photometric measurements of SN 2001ke compared with early observations of SN 1998S. The *HST* fluxes (circles) have been corrected for our adopted extinction. The fluxes for SN 1998S (lines) have been corrected for $A_V = 0.12$ mag, redshifted to $z = 0.36$ and then scaled to approximately match the early *HST* photometry. The times given for SN 1998S are in rest-frame days after V-band maximum light.

of SN 1998bw does not fit the 2001ke light curve well. Another type Ic hypernova, SN 2002ap (Mazzali et al. 2002), appeared to evolve more quickly than SN 1998bw, however, there is no associated GRB to set the time of explosion and it appears to be significantly less luminous than either 1998bw or 2001ke.

This early maximum combined with a blue color is surprising. Type II supernova rise quickly, but their hydrogen envelope traps energy and makes them fade more slowly than observed for 2001ke. Possibly the hydrogen envelope was small or non-existent and the circumstellar phase relatively short as was the case for SN 1993J. Of course, the supernova may have exploded days before the GRB detection as has been proposed to explain metal absorption lines in X-ray spectra of some GRB. Supernova 1998bw would fit $R/F702W$ data well if it went off ~ 7 rest-frame days before the GRB. Assuming the GRB may not signal core-collapse, we still conclude that SN 2001ke was not identical to SN 1998bw and that a range of supernova types can produce GRB.

GRB 011121 is an exciting new link connecting the fields of GRBs and supernovae, but it also represents something of a missed opportunity to study this link in detail. Prompt and reliable reduction of the *HST* data for this burst (taken when the supernova component was relatively bright) would have most likely enabled the astronomical community to obtain significantly more information about the SN, including better spectroscopy and perhaps polarimetry. Given that this was the lowest redshift GRB and afterglow discovered to date (over more than four years of intense efforts), the community should take care that similar oversights are not repeated in the future.

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Table 1. Local Standard Star Magnitudes

Star	U	B	V	R	I	J
A	···	20.00	18.91[a]	18.20	17.58	···
B	17.20	···	···	···	···	···
C	···	21.39	···	20.00	19.45	···
D	···	21.03	···	19.26	18.63	17.83
E	···	21.87	···	20.06	19.39	18.62
F	19.61	19.13	···	···	16.70	···
G	20.32	20.09	···	18.40	17.77	···
H	18.39	18.21	···	···	16.22	···
I	19.98	19.94	···	18.42	17.83	···

[a]From Olsen et al. 2001

Table 2. GRB 011121/SN 2001ke Photometry

UT Date (2001)	Age (days)	Filter	Magnitude	Telescope
Nov 22.2149	0.4323	*R*	19.06 (03)	OGLE 1.3m
Nov 22.2214	0.4388	*R*	19.09 (03)	OGLE 1.3m
Nov 22.2519	0.4693	*I*	18.55 (03)	OGLE 1.3m
Nov 22.2637	0.4811	*V*	19.87 (03)	OGLE 1.3m
Nov 22.2714	0.4888	*R*	19.26 (04)	CTIO 0.9m
Nov 22.2796	0.4970	*R*	19.31 (03)	CTIO 0.9m
Nov 22.2824	0.4998	*B*	20.68 (08)	OGLE 1.3m
Nov 22.2871	0.5045	*I*	18.61 (03)	CTIO 0.9m
Nov 22.2947	0.5121	*B*	20.71 (06)	CTIO 0.9m
Nov 22.3021	0.5195	*V*	20.00 (04)	CTIO 0.9m
Nov 22.3057	0.5231	*R*	19.45 (03)	OGLE 1.3m
Nov 22.3121	0.5295	*V*	20.05 (05)	OGLE 1.3m
Nov 22.3183	0.5357	*I*	18.81 (03)	OGLE 1.3m
Nov 22.3265	0.5439	*R*	19.50 (03)	OGLE 1.3m
Nov 22.3357	0.5531	*V*	20.16 (04)	OGLE 1.3m
Nov 22.3452	0.5626	*U*	20.46 (15)	CTIO 0.9m
Nov 22.3454	0.5628	*I*	18.86 (03)	OGLE 1.3m
Nov 22.3542	0.5716	*R*	19.59 (03)	OGLE 1.3m
Nov 23.2400	1.4574	*I*	20.60 (10)	OGLE 1.3m
Nov 23.2679	1.4853	*V*	21.19 (10)	OGLE 1.3m
Nov 23.3149	1.5323	*R*	21.41 (05)	Baade 6.5m
Nov 23.3177	1.5351	*R*	21.43 (04)	CTIO 4m
Nov 23.3201	1.5375	*R*	21.40 (06)	Baade 6.5m
Nov 23.3231	1.5405	*B*	22.86 (06)	CTIO 4m
Nov 23.3327	1.5501	*U*	22.40 (20)	CTIO 4m
Nov 23.3450	1.5624	*I*	20.86 (03)	CTIO 4m
Nov 24.361	2.578	*R*	22.24 (12)	Baade 6.5m
Nov 29.31	7.53	*J*	22.31 (15)	Baade 6.5m
Nov 30.30	8.52	*J*	22.09 (15)	Baade 6.5m
Dec 1.30	9.52	*J*	22.11 (15)	Baade 6.5m
Dec 4.33	12.55	*R*	23.07 (15)	Baade 6.5m
Dec 4.90	13.12	*F*450*W*	24.67 (13)	*HST*
Dec 4.97	13.19	*F*555*W*	23.87 (10)	*HST*
Dec 5.04	13.26	*F*702*W*	23.14 (07)	*HST*
Dec 5.33	13.55	*R*	23.11 (12)	Baade 6.5m
Dec 5.83	14.05	*F*814*W*	22.78 (08)	*HST*

Table 2—Continued

UT Date (2001)	Age (days)	Filter	Magnitude	Telescope
Dec 5.94	14.16	$F850LP$	22.78 (13)	*HST*
Dec 6.35	14.57	R	23.23 (15)	Baade 6.5m
Dec 7.31	15.53	R	23.19 (15)	Baade 6.5m
Dec 9.06	17.28	R	23.10 (13)	Baade 6.5m
Dec 14.82	23.04	$F555W$	24.51 (11)	*HST*
Dec 14.88	23.10	$F702W$	23.37 (08)	*HST*
Dec 16.64	24.86	$F814W$	23.12 (10)	*HST*
Dec 16.75	24.97	$F850LP$	22.73 (13)	*HST*
Dec 19.02	27.24	$F555W$	25.02 (12)	*HST*
Dec 19.08	27.30	$F702W$	23.66 (10)	*HST*
Dec 19.89	28.11	$F814W$	23.21 (10)	*HST*
Dec 19.95	28.17	$F850LP$	22.78 (13)	*HST*